Adaptive Power Control with Vehicular Trellis Architecture for Vehicular Communication Systems

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***Abstract*—Autonomous driving in future vehicle system has imposed a high demand for reliable and power efficient communication to provide safe-driving to vehicular users. In order to achieve reliability and power efficiency, in this paper, a vehicular trellis architecture (VTA) is proposed. VTA allows traffic information to be transmitted either via vehicle-to-infrastructure (V2I), through the dedicated remote radio head (RRH) and its dynamically select vehicle(s) or, direct vehicle-to-vehicle (V2V) communication. We investigated the adaptive switching over V2I/V2V, to enhance efficient system reliability while optimizing the average power consumption of VTA. This paper presents a vehicular trellis algorithm (VTRA), which approximate solutions to the optimization problem. Simulation results demonstrate that the selection of joint V2I/V2V communication reduces the total power consumption of the system for a varying number of threshold distance and vehicles.**

***Index Terms*—Beam. RRH, GA, V2V, V2I, V2X, Trellis.**

I. Introduction

The integration of communication technology in state-of-the-art of vehicles is being investigated as an effective solution to improve the safety and reliability in connected autonomous driving [1]. The variations in reliability demands across the coverage area of a wireless vehicular network and infeasibility to exactly adopt a grid-based deployment for vehicular networks have introduced uncertainties to the average power allocation in vehicular communication. Higher reliability requires having several low-power transmissions rather than one high-power transmission as shown in [2]. Many existing works have considered coexistence paradigm of vehicular networks. Authors in [3] demonstrated an improved beaconing resource occupation by exploiting a long term evolution (LTE) for V2V beaconing without downlink resources. [4] adopted context-aware sidelink communication scheme with static massive machine-type communication (mMTC) user equipment to improve the power usage for mMTC. V2V communication between two neighbouring vehicles also contributes to higher system capacity by re-using the LTE resources [5]. Whereas [4] cannot be applied directly to V2V systems, and [5] aggravates the already significant signalling overhead in [4]. An LTE Cellular-Based V2X was proposed in [6] to improve the communication performance of vehicles, mainly with LTE network assistance over direct communication between vehicles. Consequently, the study of the vehicular communication system architectures for achieving high reliability along with power allocation is vital. However, none of these works has adequately addressed the impact of adaptive communication over V2I and/or V2V to guarantee a power optimized reliable system. Genetic Algorithm (GA), is a stochastic algorithm based on the principles of natural selection, applied in machine learning and optimization problems [7]. A trellis structure is a representation that implement maximum likelihood of an event with the use of Viterbi algorithm to reduce system complexity [8] and deals with the concept of minimum distance, weight distribution and distance profile. Therefore from the above research observations, the coexistence of V2V communications with little or no cellular-assisted V2I communication have not been thoroughly investigated. In this paper, we propose a vehicular trellis architecture (VTA) into a systematic and efficient vehicular communication solution methodology for connecting available vehicles through dedicated remote radio head (RRH) [9], [10], [11], [12], [13] for V2I communication. Our aim is to promote an effective deployment of V2I communication to guarantee reliability over adaptive power control by the selection of shortest communication link through joint RRH-vehicle/V2V communication. In order to accomplish the VTA, we further propose a vehicular trellis algorithm (VTRA). VTRA is a hierarchical hybrid algorithm comprising parallel GA and trellis-based algorithm for the purpose of power minimization solutions. VTRA is based on adaptive heuristic search method to produce shortest path routing due to a global search capability. The dedicated RRH features mmWave-MIMO antenna configuration. mmWave MIMO communication demonstrates enhanced power efficiency at high carrier frequencies, and high transmission quality [14]. The dedicated RRH is low cost and can replace the conventional full-functionality small base stations (SBS) for the purpose of low-complexity vehicular transmission and reception.

- We investigate VTA for system reliability and accommodate power control requirements, while selecting the least power consuming joint V2I/V2V association pattern, between RRH and vehicles. We propose VTRA for joint optimization solution of RRH-V2V power control for VTA based on GA for optimization. We compare the power consumption for conventional schemes and our proposed solution, which allows every vehicle to communicate with its neighbouring vehicles within a threshold distance.
- We formulate the optimization problem of minimizing the total power consumption in the VTA, which can adapt the RRH-vehicle link and V2V link for transmitting critical traffic information. This optimization problem requires

joint optimization of RRH-vehicle link and V2V links.

II. System Model

Consider a network model of a dedicated RRH and vehicular units located at a traffic intersection as shown in Fig. 1. The RRH can be stand-alone or co-located with an existing traffic infrastructure and consists of antenna arrays, which can form a beam per vehicle to accommodate the aggressive spatial multiplexing and can support coordination with other RRHs, via high speed transport links (backhaul link). Each vehicle houses dual-antenna aided on-board unit (OBU) transceiver for independent and simultaneous communication for V2I and V2V at different respective frequencies. We assume that all link experience slow fading effect due to multipath and shadowing due to low vehicle speed required at a traffic intersection. RRH antennas are positioned to serve available vehicles located within a predefined coverage region, d_Z, on a single lane road segment at any instance of time. We assume that although both forward and backward V2V transmissions are possible, but we consider only a single V2V transmission within a time frame. For the purpose of simplicity, V2I and RRH-Vehicle are used interchangeably.

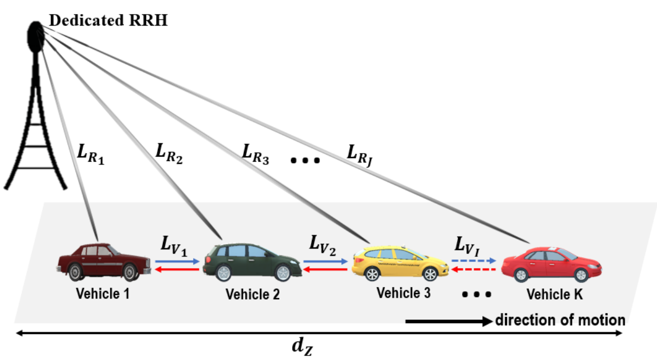

Fig. 1. System model of VTA for a RRH serving vehicles in a single traffic lane

A. Channel Models for RRH-Vehicle and V2V Communications

Let $\mathcal{M} = \{M_j \mid j = 1, 2, \cdots, J_M\}$ be the set of RRH antenna for RRH-vehicle V2I communication, where J_M is the number of active RRH-vehicle link by active RRH antenna chain to accommodate a line-of-sight (LOS) communication. Let $\mathcal{K} = \{K_i \mid i = 1, 2, \cdots, I_K\}$ be the set of vehicle for both RRH-vehicle V2I pair at f_1 and V2V pair at a centre frequency, f_2, with a distance threshold, d_{th}, between two vehicles (V2V), where I_K is the number of V2V active links at an instance of time. we assume a negligible interference between V2I and V2V as different frequencies are considered for V2I and V2V communication respectively. The channel matrix is denoted by $\mathbf{H} = \left[\mathbf{h}_1^T, \cdots, \mathbf{h}_k^T, \cdots, \mathbf{h}_K^T\right]^T$ and $\mathbf{h}_k$ represents the Rician channel matrix between the m-th RRH and k-th OBU. We adopt the close-in (CI) mm-Wave propagation model in [15], [16] for both V2V and V2I, written as $PL(f_1, d)[dB] = 20\log_{10}(4\pi f_1/c) + 10n\log_{10}(d) + X_{\sigma_{SF}}$, where c is the speed of light (m/s), d is the distance (m) which is the ratio of Tx-Rx distance d_T, and reference distance d_o is 1m. n is the pathloss exponent, and $X_{\sigma_{SF}}$ is the shadow fading (SF) which is a zero-mean Gaussian distribution, with a standard deviation of σ_{SF}. V2V channel is by nature different from cellular and many other radio channels. Due to mobility, the Rician channel, h_k, changes fast. As a result of this, the channel, h_k between Tx and Rx is relative to the distance apart [15], [16] and it is represented by

$$h_k = \sqrt{\frac{1}{\rho}} \sum_{l=1}^{L} \alpha_l \, \delta \left[t - \tau_l(t)\right], \tag{1}$$

where at time t, α_l is the path amplitude of the l-th resolved path, $\tau_l(t)$ is the time varying delay for the l-th path, ρ is the pathloss, δ is the Dirac delta function and L is the number paths. The multipath channel leads to frequency selective fading channel [17], [18], [19].

Introducing beamforming at RRH, we proposed the minimum mean square error (MMSE) to eliminate inter-beam interference e.g. RRH-vehicle 1 and RRH-vehicle 2. The aggregated received signal model for the k-th vehicle is given as

$$\mathbf{y}_k = \mathbf{h}_k \cdot \mathbf{x}_k + \sum_{k \neq i} \mathbf{h}_k \cdot \mathbf{x}_i + \mathbf{n}_k \tag{2}$$

where $\mathbf{x}_k$ is the signal vector transmitted by the RRH antenna array with beamforming. $\mathbf{n}_k$ is the noise vector, which is an additive Gaussian noise vector that follows i.i.d. $n_k \sim \mathcal{N}\left(0, \sigma_n^2\right)$ for the k-th vehicle.

The radar cross section (RCS) enhancing measure is a potential interference generation phenomenon and it is applicable to signal reflection when a signal strikes the surface of an auto mobile or other manufacturer coupled reflectors. Radar signal, up to 25dB, results from reflected energy from various portions of the vehicle [20]. The signal towards a time-variant moving vehicle is reflected with a frequency shift when rays interact on a rough surface of moving objects. Interference between V2V links can be expected due to reflections, through reflecting objects, such as the guardrails, and this degrades gradually when V2V distance increases. The signal-to-interference-plus-noise ratio (SINR) is represented by

$$\gamma_\eta = \frac{\sum_{k=1}^{K} P_\phi^T h_\eta}{\underbrace{\mathbb{E}\left(\sum_{m \neq m'}^{M} P_{m',k}^T h_m\right)}_{\mathrm{I}_m} + \underbrace{\mathbb{E}\left(\sum_{k \neq k'}^{K} P_{k,k'}^T h_k\right)}_{\mathrm{I}_k} + \sigma_k^2} \tag{3}$$

I_m and I_k are the expected interfering reflected signals from neighbouring RRH and vehicle respectively. h_m and h_k are the interfering ray gain due to m-th RRH and k-th vehicle respectively. $P_{m',k}$ and $P_{k,k'}$ represent the transmit power of the neighbouring RRH and vehicles respectively. σ_k^2 is the AWGN noise power of the receiver.

$$\eta = \begin{cases} 1 & \text{for V21 link,} \\ 2 & \text{for V2V link,} \end{cases}$$

η = 1 for V2I received SINR and η = 2 for V2V received SINR. $\phi \in \{m, k\}$ i.e. ϕ = m for the transmit power, P_m^T, of the m-th RRH during V2I communication and ϕ = k for the transmit power, P_k^T, of k-th vehicle during V2V communication. The achievable rate, in bits/sec, for all existing channels, with B_η as the channel bandwidth is denoted as

$$R_\eta = B_\eta \log(1 + \gamma_\eta). \tag{4}$$

where B is the bandwidth and $\eta \in \{1, 2\}$ i.e. η = 1 for the V2I achievable rate and η = 2 for the V2V achievable rate. We apply φ_η as the channel utilization, whereby φ_1 is the channel utilization between m-th RRH and k-th vehicle within the coverage of the RRH; φ_2 is the channel utilization between k-th vehicle and $k^{'}$-th vehicle for V2V communication within the coverage of the RRH. This is formulated as

$$\varphi_\eta = \frac{\beta_\eta}{R_\eta}$$

where β_η represents the required data rate at time t i.e. β_1 and β_2 represent the required data rate for V2I and V2V communications respectively.

III. VTA: V2I Downlink and V2V Optimization Requirement

The RRH and vehicles accommodate different quality of service (QoS). Our proposed VTA solution focuses on optimizing the system power consumption to improve system reliability at V2I and V2V link, as long as the transmission distance thresholds are satisfied.

A. Power Control Optimization

A reliable communication system is highly sensitive to power consumption. The energy/reliability correlation demands that decoupling a high-power transmission into several low-power transmissions can guarantee higher system reliability.Our objective is to optimize the total V2X system power consumption per RRH-vehicle and/or V2V communication link with the aid of joint optimization of V2I and V2V communication links. For all existing V2V pairs, the received power is assumed to be constant and V2V links are considered to be Line-of-Sight (LOS). For V2V, the adaptive transmission power, P_k^T, is assigned at the k-th vehicle in order to overcome ψ pathloss fraction respect to a reference received power, P_0^R, which is limited by the maximum transmit power of a vehicle and can be represented as

$$P_k^T = \min\left\{P_{max}^T, \frac{P_0^R}{\psi * \rho^{v2v}}\right\} \tag{5}$$

where P_k^T, P_{max}^T, P_0^R represent k-th vehicle V2V transmit power, k-th vehicle V2V maximum allocated power and the received power at the receiver for V2V communication. ρ^{v2v} is the pathloss and ψ is a constant. We assume that all channel gains are independent of one other, independent of the spatial locations and are i.i.d across all links. The total transmit power of a m-th RRH is dependent of the spectral resources allocated to the m-th RRH and its pathloss. Each RRH is assumed to consume a constant power of 33dBm (P_m^T) at a coverage distance less than 20 metres across all traffic load.

IV. Problem Formulation

We formulate the joint power optimization problem for VTA to fulfil the reliability requirements for V2V and V2I simultaneously. We detail the joint power optimization problem for VTA, which fulfils the designed requirements of all communications entities. The total system power consumption considered in this paper can be represented as:

$$\begin{aligned} P_{total} &= P_{RRH} + \sum_{k=1}^{K} P_k^T \\ &= KP_S + \sum_{k=1}^{K} P_m^T + KP_{RF} + P_{BB} + \sum_{k=1}^{K} P_k^T \end{aligned} \tag{6}$$

where P_{RRH} is the total RRH power, comprising (i) P_S: the symbol power, (ii) KP_{RF}: power consumed by each RF chain at m-th RRH, (iii) P_{BB} is the power consumed by MMSE precoder at the m-th RRH, and (iv) transmit power. The VTRA for the joint optimization performs an adaptive heuristic search, adaptively select and combine preferred V2I and V2V shortest path communication link, by incorporating dynamic power consumption of the RRH and transmit power of each vehicle due to RRH-vehicle and V2V communication links. The optimization problem is formulated as follows:

$$\min\left[\sum_{k=1}^{K}(\varphi_1 * P_{RRH} * \mathit{\Phi}_m) + \sum_{k=1}^{K}\left(\varphi_2 * P_k^T * \mathit{\Phi}_k * \mathit{\Phi}_m\right)\right] \tag{7}$$

$$\text{C1: } R_1 * \mathit{\Phi}_m \geq \beta_1 \qquad m \in \{1, \cdots, M\} \tag{7a}$$

$$\text{C2: } R_2 * \mathit{\Phi}_k \geq \beta_2 \qquad k \in \{1, \cdots, K\} \tag{7b}$$

$$\text{C3: } d_v * \mathit{\Phi}_k \leq d_{th} \qquad k \in \{1, \cdots, K\} \tag{7c}$$

$$\text{C4: } \sum_{k=1}^{K}(\varphi_1 * \mathit{\Phi}_m) \leq K \quad k \in \{1, \cdots, K\} \tag{7d}$$

$$\text{C5: } \mathit{\Phi}_m, \mathit{\Phi}_k \in \{0, 1\} \tag{7e}$$

where M is the number of RRH antenna chain, K is the number of vehicle. $\mathit{\Phi}_m$ and $\mathit{\Phi}_k$ are binary variables which takes the values of 1 in case of association of m-th RRH to k-th vehicle in V2I and k-th vehicle to $k^{'}$-th vehicle in V2V respectively and 0 otherwise at time t. d_v and d_{th} are the V2V Tx-Rx distance and threshold distances respectively. Constraint (7a) indicates that the achievable rate by the vehicle k in V2I is greater or equals the demanded data rate, β_1. Constraint (7b) indicates that the achievable rate by $k^{'}$-th vehicle for V2V communication is greater or equals the required data-rate, β_2, within RRH coverage region. Constraint (7c) specifies that distance between k-th vehicle and $k\prime$-th vehicle is less or equals the V2V threshold distance value, d_{th}. Constraint (7d) indicates that k-th vehicle that can be served by RRH in V2I is less or equals the number of RRH antenna, M. Constraint (7e) specifies the decision variables of the formulated problem, $\mathit{\Phi}_m$ which takes a value of 1 if there exists a V2I link and 0 otherwise. $\mathit{\Phi}_k$ is 1 if there exists a V2V pair within the RRH coverage region and 0, otherwise.

A. Vehicular Trellis Algorithm (VTRA)

VTRA is an optimization algorithm based on adaptive heuristic search method to produce shortest communication path routing due to a global search capability. VTRA maintains the number of vehicles within the coverage region and probabilistically modifies the selection operation with the intent of seeking a near-optimal solution of preferred transmission pattern. Algorithm 1 shows the flow chart for proposed VTRA. Received power is a function of the pathloss, which is directly related to distance between the transmitter and receiver.

Algorithm 1 Vehicular Trellis Algorithm (VTRA)

1: **Input:** $\mathcal{M} = \{M_j \mid j = 1, 2, \cdots, J_M\}, \forall m \in M$, $\mathcal{K} = \{K_i \mid i = 1, 2, \cdots, I_K\}, \forall k \in K, \Phi_m \geq 1, \Phi_k \geq 1$
2: **for** $m = 1$ **to** M **do**
3: compute $d_R = \underset{M_j \in \mathcal{M}, K_i \in \mathcal{K}}{\operatorname{argmin}} \{d_{M_j,K_i}\}$
4: **for** $k = 1$ **to** K **do**
5: compute $d_V = \underset{K_i, K_{i^*} \in \mathcal{K}}{\operatorname{argmin}} \{d_{K_i,K_{i^*}}\}$
6: Execute heuristic search and select shortest path, using GA.
7: **end for**
8: **end for**

V. Simulation and Performance

This section evaluates the performance of the optimum RRH-vehicle/V2V links at different communication threshold distances and QoS in the adaptive VTA. The performance of the GA algorithm is assessed by means of Matlab. As shown in Fig. 1, a dedicated RRH with M = 4 antennas and $K = 4$ dual-antenna aided vehicles are deployed for vehicular mobility in a single direction of motion as shown in Fig. 1. Vehicles travel along defined road segment length d_z with an average speed of 15km/h. In trellis representation, each path represents a signal link. This representation aids implementation of maximum likelihood link path with the aim of optimizing total transmission power. The vehicles are located at distances of $L_{R_1} = 20$m, $L_{R_2} = 40$m, $L_{R_3} = 80$m and $L_{R_4} = 100$m with respect to the reference RRH. The vehicles are $L_{v_{1,2,3}} = 20$ meters apart i.e. 20 meters equidistant. We investigate the effect of adaptive V2V/V2I TX power control and maximum system power consumption for different distance thresholds between RRH and $K = 4$ vehicles. Four vehicles per RRH, i.e. 4 links, can generate up to 24 possible transmission patterns. A transmission pattern denotes that 4 vehicles receive the information message through joint V2I and V2V, $({}^4P_3)$, to satisfy all constraints. In Fig 1, blue lines denote forward V2V transmission, and red lines denote backward V2V transmission. V2I transmission is represented by grey beam/ray lines. Fig. 2 represents 4 out of 24 possible transmission trellis patterns.

Table I describes the simulations parameters. Simulation results for network capacity as well as power consumption are

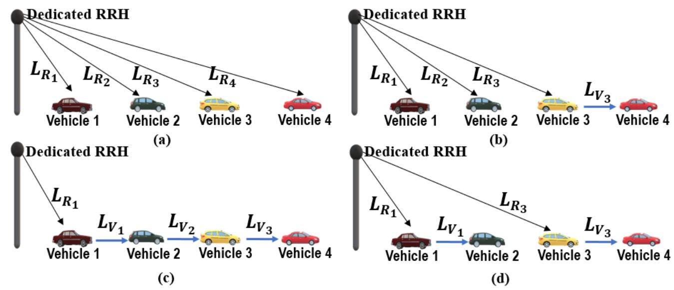

Fig. 2. 4 of 24 possible trellis transmission patterns. $M = 4.K = 4$

TABLE I
COMPUTATIONAL PARAMETER.

Notation	Parameter
Carrier Frequency Band	60 GHz (f_1) 5.8 GHz (f_2)
System Bandwidth	1GHz for 60GHz 30 MHz for 5.860 GHz
Noise Variance	-174 dBm/Hz
TX Power	33dBm for RRH 30dBm for vehicle
Antenna height	2.5 m for RRH; 1.2 m for vehicle
Number of vehicles (K)	4
Number of Antenna	4 for RRH; 2 for vehicle
Path-loss Model	3D Urban Micro
V2I/V2V Data Rate Demand	800 Mbps/750 Mbps
RF Chain (P_{RF})	250 mW
MMSE Precoder P_{BB}	250 mW

attained strictly with respect to threshold distance and the other constraints based on our proposed VTA.

Fig. 3 plots the consumed power values for $J_M = 4$ beams/rays, $K = 4$ vehicles. 100000 Monte-Carlo [17], [18], [19] iterations are performed to simulate the position uncertainty of vehicles and hence of link paths. In Fig. 3, it can be observed that the minimum and maximum transmit power for $L_{R_1} = 20$m and $d_{R_4} = 100$m V2I distances are 3Watts and 3.85 Watts when all V2I and V2V links are active before the joint optimization. It is clearly seen that the joint optimization effect of GA minimizes the total system power consumption in association with V2V communication. However, the system power consumption irrespective of the optimization tends to be increasing. This is due to increasing V2I distance i.e. L_{R_1}, L_{R_2}, L_{R_3} and L_{R_4}.

Fig. 4 shows a relationship between the total system power consumption for a maximum of 4 associated link paths L_{R_1}, L_{R_2}, L_{R_3} and L_{R_4} before and after optimization. Clearly, our proposed joint power optimization reduces the power consumption for every associated link path. Fig. 4 also shows that RRH-vehicle communication is preferred when the number of RRH chain equals the number of vehicles. This is because as the number of RRH-vehicle association increases, the V2V association gradually decreases. This impacts on the total power consumption wherein the power consumption is observed to have been minimized i.e. as the V2V association gradually decreases, the total system power decreases. This is subject to the application of joint power consumption as it can be clearly seen in Fig. 2 that the maximum RRH-vehicle TX power is recorded as 3.85Watts and then minimized to approximately

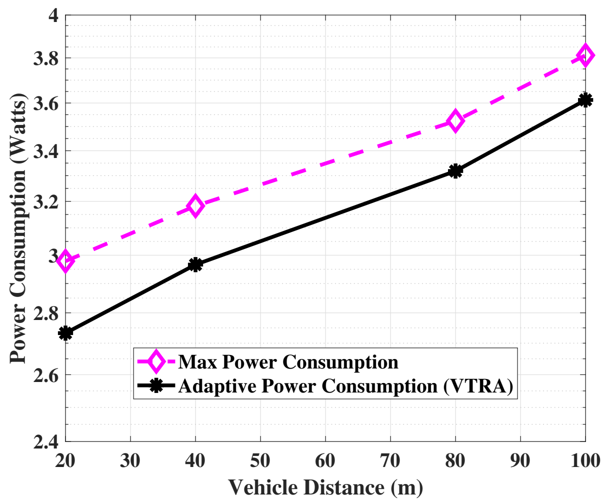

Fig. 3. Power consumption with vehicle distance. $M = 1.N = 4.K = 4$

3.03watts in Fig. 4 when RRH-vehicle association equals 3 i.e. three V2I associations and one V2V association (Fig. 2(b)).

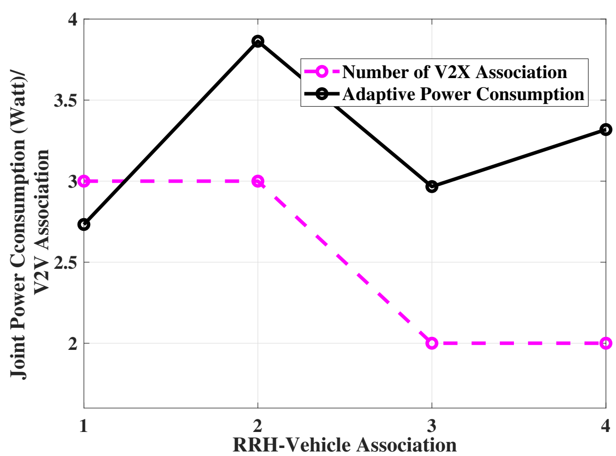

Fig. 4. Joint power consumption with V2V association. $M = 1.N = 4.K = 4$

VI. Conclusion

This paper has presented the performance and operation of joint RRH-vehicle/V2V power optimization. This paper proposed VTRA, which accounts for application of GA and vehicle localization to search for a near-optimal solution of shortest transmission path via joint RRH-vehicle and V2V communications. Simulation results demonstrate that joint optimization minimizes the total power consumption of the system. For future work, we propose to develop a heuristic algorithm to solve the optimization problem incorporating existing cellular networks with channel estimation and analyze the performance of our heuristic.

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